PATENT

PREFERENTIAL FRACTURING OF SOIL AND MATERIAL IMPLANTATION

BACKGROUND OF THE INVENTION

1. Field of the Invention:

This application is a continuation-in-part of Application Serial Number 09/324,700, filed June 2, 1999, entitled Formation of Subsurface Barriers in Soil.

The present invention relates generally to a method to place a substantially single and continuous fracture in soil at a controlled location. Such a fracture can be placed at varying depth and cover a broad area. The fracture can also be filled with various materials to create a layer in the soil that can be used for various purposes. Hence the fracture method allows a layer of material to be placed, *in situ*, without disturbing the overbearing soil.

1a. Definitions

For purposes of this invention, the following definitions apply.

Fracturing is the process of creating a discontinuity in the soil.

Preferential fracturing is the process of fracturing soil at selected and predetermined locations with the fracture occurring over a broad area and forming substantially a single and continuous fracture. A preferential fracture is the resulting fracture from the preferential fracturing process.

Fracture plane is the area and path of the created fracture (discontinuity) in soil. The fracture plane will have naturally occurring undulations but can also be contoured

based on the locations and orientations of installed stress concentration cavities used to create and control the fracture plane.

A barrier is a subsurface layer of material placed into the soil. The barrier may have many different characteristics depending on the material implanted (barrier fluid material).

Barrier fluid is a fluid material that can be injected into soil fractures and will flow along the fracture plane to form a layer of material in the soil with the desired thickness and material characteristics, after the barrier fluid has cured or set or solidified.

Control zone is the area over which the fracture process is to be controlled. It is the area in which stress concentration cavities are created so that the preferential fracturing occurs at the desired location.

Conduit is a channel for conveyance of tools and fluids into the soil. Conduits are shafts, boreholes, tubes, pipes, etc., for purposes of this invention.

2. Discussion of Background:

There are currently many thousands of polluted sites nationwide. Many of these are designated waste sites, former dumping grounds, storage ponds, and underground tanks; others are the result of inadequate process control, chemical spills and the like. Containment and remediation efforts are underway at many of these sites, particularly large, severely contaminated sites that contain hazardous materials. Other sites pose no immediate threat to the surrounding ecosystem and are left untreated; still others are too small or diffuse for cost-effective treatment by presently

available technologies. However, the migration of contaminants from these sites into local water supplies and soil could pose serious health and environmental concerns.

Many approaches have been implemented to treat contaminated sites. Contaminated soils can be excavated, treated to remove pollutants, and returned to the site or simply stored elsewhere. Groundwater may be removed along with excavated soil or be pumped to the surface for treatment. These direct methods of dealing with contaminated groundwater are time-consuming, costly, and for many sites, not cost-effective.

Another approach is to contain or isolate a contaminated site in order to limit the spread of contamination into the surrounding soil and groundwater. For example, liners of clay, cement or plastic may be placed around and under ponds and storage tanks to control seepage. This approach is most useful if the liner can be installed during construction of the site (that is, before the release of contaminants), since it can be difficult to retrofit an existing pond or install a liner to contain contaminants that have already spread beyond the initial site.

A number of other techniques are available for controlling the migration or flow of fluids, thereby isolating an underground region. For example, the system described by Paurat, et al. (U.S. Patent No. 5,199,816) includes a tunnel situated in the ground beneath a dump. An array of drainage pipes surrounds the dump, each pipe having an upper end at the surface and a lower end opening into the tunnel. A mixture of drilling mud and Portland cement is injected into the ground via the pipes to form a barrier. Kingsbury (U.S. Patent No. 4,439,062) shows a multilayer seal that includes two layers of water-expandable colloidal clay separated by a layer of granular fill material. Klie (U.S. Patent No. 1,987,626) provides a process and apparatus for filling cracks in concrete, rocks and the like with a plugging material.

A variety of fluids can be injected into an underground formation to form a barrier, including sodium silicates, resins, and polyacrylamides (Gadelle, et al., U.S. Patent No. 4,705,431); grout and two-component catalytically setting resins such as epoxy or polystyrene (Colgate, U.S. Patent No. 4,370,077); metal alkoxide compositions in a nonvolatile, oil-soluble dispersing agent (Sparlin, et al., U.S. Patent No. 3,915,727); asphalt, cement, polymers, and silicates (Coffer, et al., U.S. Patent No. 3,407,605); a liquid holding a suspension of a gelatinous or colloidal precipitate such as silicate of soda or sulphate of alumina (François, U.S. Patent No. 1,430,306); and gelling agents (aluminum naphthenate, gums, etc.) dispersed in a hydrocarbon oil (Wyllie, U.S. Patent No. 3,062,286).

Directional drilling combined with soil fracturing techniques are used in the mining industry for the isolation and recovery of ores. Fracturing creates multiple cracks and passages in the strata surrounding the boreholes, facilitating greater penetration of grout or other sealants into the strata. Huff, et al. (U.S. Patent No. 5,030,036) drill a grid of vertical boreholes in the contaminated region, lower hydraulic packers into the boreholes, then separately fracture the strata surrounding each borehole in a local and uncontrolled manner by injecting high pressure fluid through the packers into the bottom ends of the boreholes. This procedure creates a random pattern of multiple fractures radiating from each of the boreholes. Soil penetrating fluid is injected into the fractures to form a barrier. The multitude of random and uncontrolled fractures will consume very large quantities of expensive material without assurance of effectiveness.

Grable (U.S. Patents 4,651,824 and 4,637,462) discloses positioning a tube longitudinally in a borehole, rotating the tube to orient an opening azimuthally, and firing a projectile through the opening into a selected lateral zone to open up a lateral shot hole. No fracturing is performed.

Fracturing techniques followed by fluid injection are used by Schuring (5,032,042), Oudenhoven (U.S. Patent No. 4,394,051), Tregembo, et al. (U.S. Patent No. 3,690,106), Coffer, et al. (U.S. Patent No. 3,407,605), and Wyllie (U.S. Patent No. 3,062,286). However, none of these methods uses preferential fracturing over a broad area to create substantially one major fracture in a controlled and selected location.

Cleary (U.S. Patent No. 4,230,368) and Pratt (U.S. Patent No. 703,302) describe fracturing techniques for elevating solid masses (blocks of earth or stone), but not for creating a barrier by a controlled fracture over a broad area. Cleary isolates large blocks of earth by any of a variety of techniques, including drilling, jetting, fracturing and kerf cutting. He then injects a slurry through vertical injection wells to separate the blocks from the surrounding earth. The slurry may contain sodium bentonite, gelled asphalt, carboxymethyl cellulose and other polymers, sand, silt and clay. Pratt uses explosives and fluid pressure to form a bed-seam under a sheet of stone to be excavated. Fracturing may be enhanced by injecting a cooling fluid into the soil, then injecting a fracturing fluid at a pressure sufficient to initiate fractures in the cooled region (Emery, U.S. Patent No. 4,476,932; Perkins, U. S. Patent No. 4,589,491).

Constructing a subsurface barrier by means of any of the above-described techniques requires the presence of special soil conditions in addition to a substantial commitment in both materials and labor. Without controlling the extent of the fractures, or containing the fractures within strata, the soil tends to fail as by crack extension (an uncontrolled manner as noted by Oudenhoven, U.S. No. 4,394,051). Furthermore, such barriers are typically constructed without significant control of placement and depth; therefore, they vary vastly in thickness, relative locations, continuity, and effectiveness.

Known techniques for constructing subsurface barriers are inefficient in terms of materials usage, and do not ensure production of a continuous barrier in all types of soil. For example, Huff ((U.S. Patent No. 5,030,036) applies pressure at one point at a time without control of the soil stress and hence produces a multitude of fractures but with no control over where the fractures will occur or travel. Thus, his barrier includes a pattern of individual fractures that may not be connected. Connectivity can possibly be achieved by seepage of very large quantities of barrier fluid into the soil; however, formation of a continuous barrier is not assured. To form an effective barrier, these types of methods require very large amounts of barrier fluid. Coffer (U.S. Patent No. 3,407,605) injects a barrier fluid into a specific, permeable layer of soil. This type of fracturing is uncontrolled; indeed, the fractures may not even follow the contours of the underlying strata. If not controlled in some manner, the resultant fracture would not occur over a broad area but could occur as long fingers that could reach in many directions; hence, the fracture would not be effective in forming a barrier. François (U.S. Patent No. 1,430,306) does not preferentially fracture soil for the purpose of injecting a barrier fluid in a selected location: his two-step process is used to fill an existing fissure in water-bearing strata.

Despite the wide range of presently available methods and materials used for treating contaminated sites, there remains a need for an efficient, cost-effective method for placing *in situ* a layer of material about a selected subsurface region. Such a layer of material could be used for various purposes such as a barrier, filter, collector, or dispersion layer. When used as a barrier, the layer could reduce the flow of contaminants out of a contaminated region to an acceptable level, while treatment, or *in situ* degradation of contaminants occurs. Such a barrier could also be useful for other applications such as retention of moisture and nutrients in soil.

It is assumed that a barrier would be a typical application for this process and hence for simplification, reference is made to a barrier and barrier fluid in this specification.

OBJECTIVES AND ADVANTAGES

The objective of this invention is the formation of a substantially single and continuous fracture in soil, with the fracture location controlled as to depth and area. The fracture can than be filled with a layer of material to form a barrier, *in situ*, such a barrier having the desired and planned characteristics.

The advantages of this process are many and include control of the specific location of the barrier, ease of placement, a substantially a single and continuous barrier layer, and the ability to contour the barrier to achieve the desired performance. These advantages lead to other advantages such as a low cost for installation and low cost for material because essentially all of the material is placed where needed. That is, no significant amount of material is deposited where it is not needed.

The current invention is a simple process, but portions must be completed in a precise manner. The creation of stress concentrations cavities in soil along the planned path of the fracture can be accomplished with simple tools and be completed in a serial manner. However the step of preferentially fracturing the soil requires synchronously stressing the soil at the stress concentration cavities to achieve the substantially single and continuous fracture necessary to effectively utilize barrier material. The preferential fracture can be accomplished in a single step and hence it is completed very quickly. Furthermore the barrier fluid can be immediately injected into the fracture and will flow along the fracture plane to rapidly create *in situ* a barrier over a broad area (control zone).

SUMMARY OF THE INVENTION

According to its major aspects and broadly stated, the present invention is a process for the controlled, efficient, and cost-effective *in situ* formation of a subsurface layer of material (barrier) in soil. Such a barrier can be formed at a specific location (depth and area) with a specific thickness. This barrier formation is achieved by first creating a network of stress concentration cavities in the soil where the subsurface barrier is to be located. The stress concentrations cavities are aligned such that when they are pressurized (stressed), the initial soil fracture is directed toward the adjacent stress concentration cavities. Accordingly, as the pressure (stress) is applied synchronously to all stress concentration cavities, the soil will fracture at about the same time at each cavity, and the fracture will propagate radially outward and connect with the fracture from the adjacent stress concentration cavities hence forming a substantially single and continuous fracture in the soil. This phenomenon occurs because the fracture has an increasing area as it propagates radially outward from each cavity and therefore the fracture fluid pressure causes an increasing lifting force on the soil above. The process takes advantage of the plasticity and cohesiveness of soil and hence lifts the overbearing soil as a single unit causing the formation of a substantially single and continuous fracture at the planned location.

The process of preferentially fracturing soil can be compared to the cutting of glass. Glass is cut by scribing a line that scores the glass and forms stress concentrations in the glass along the scribed line. Then when a load (stress) is applied to the glass in the vicinity of the scribed line, the glass will fracture along the scribed line in a controlled break (cut). That is the glass will fracture where intended, even if the desired path is curved. The aligned stress concentration cavities in the soil serve to

cause preferential fracture in soil just as the scribe (score) line causes preferential fracture in glass.

The stress concentration cavities are formed by creating shaped cavities in the soil. The stress concentration cavities are spaced throughout the region to be fractured and are created by first installing a conduit in the soil that reaches from the surface to the planned depth of the barrier. Then a stress concentration cavity is created beneath each conduit. These stress concentration cavities are shaped and aligned such that the initial fracture location and direction can be controlled. That is, the cavities are created to cause the initial fracture to propagate toward the adjacent cavities and along the planned path of the fracture.

The overall area containing the aligned stress concentration cavities in soil is the control zone because the fracture can be made to go through each stress concentration cavity and is therefore controlled in that area. Outside the control zone, the fracture will propagate in an uncontrolled manner and follow the weakest path in the soil for crack extension. To prevent unwanted travel of the fracture outside the control zone, vent holes can be installed in the soil around the periphery of the control zone. The vent holes interrupt the travel of the fracture fluid and vent the fluid to the atmosphere, hence limit the travel of the fracture. Other methods can also be used to limit the travel of the fracture such as subsurface walls or contouring the fracture so that it approaches the surface and vents the fracture fluid within the control zone.

The soil is fractured by the synchronous injection of a fracture fluid such as air or other gases. The fracture fluid rapidly discharges into each stress concentration cavity such that soil fracture is initiated in each cavity at about the same time. The fracture propagates radially outward toward the adjacent cavities and connects with the adjacent fracture to form a substantially single and continuous fracture that transverses each stress concentration cavity throughout the control zone.

Once the soil is fractures at the desired location for a subsurface barrier, barrier fluid material is injected into the fracture by way of the conduit and stress concentration cavities. The barrier fluid will easily flow along the path of the fracture. Hence a layer of material can be installed in the soil at the fracture location. A barrier of more uniform thickness can be achieved by injection of barrier fluid into all of the stress concentration cavities.

The barrier fluid is preferably a Bingham fluid, that is, a fluid that requires finite shear stress to move and hence does not penetrate significantly into the soil pores but rather flows principally along the fracture plane. Bingham fluids thereby minimizing the quantity of barrier fluid needed to form a barrier of the desired thickness and extent. Newtonian barrier fluids can be used if it is desired for the fluid to penetrate into the soil as well as flow along the fracture plane. Fluids that form porous or nonporous barriers are broadly suitable for use with the invention.

The invention allows the cost-effective placement of specialized material *in situ* and with control of material location, area, and thickness. A subsurface barrier having selected properties can be created under a broad range of soil conditions. Other features and advantages of the present invention will be apparent to those skilled in the art from a careful reading of the Detailed Description of a Preferred Embodiment presented below and accompanied by the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a cross-sectional view of a portion of a system for forming a subsurface barrier according to a preferred embodiment of the present invention. The Figure illustrates creating a fracture in soil below a region to be separated from other soil.

Fig. 2 is a top view of the system of Fig. 1, showing an arrangement of boreholes and conduits in a selected region. Other arrangements can be used.

Fig. 3 is a cross-sectional view of a portion of the barrier formed by the system of Fig. 1.

Figs. 4A and 4B are plan and cross-sectional views, respectively, of a demonstration site and equipment used to install a subsurface barrier *in situ*.

Figs. 5A and 5B are graphs of the fracture fluid (air) pressure vs. time and airflow vs. time, respectively, for the demonstration of Figs. 4A and 4B when the single and continuous fracture was created.

Fig. 6 is a cross-sectional, schematic view of the barrier installed at the demonstration site shown by Fig. 4A and 4B.

Fig. 7 is a photographic view of a portion of the demonstration site of Figs. 4A and 4B, showing the barrier in oblique view and revealing both the cross-section and the barrier surface with soil removed.

Fig. 8 is a cross-sectional, schematic view of a preferred embodiment device usable with the invention to eliminate the need for boreholes and packers.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

In the following description, like reference numerals are intended to identify the same structural elements, portions or surfaces consistently throughout the drawings, as such elements, portions or surfaces may be further described or explained by the entire written specification.

Referring to Figs. 1 and 2, there is shown an embodiment of the present invention as used in a geological formation 10 that includes soil 12 having a surface 14. Soil 12 may contain various types of materials, including but not limited to sand, clay,

gravel, stone, silt, and so forth. Region 10 includes a selected region 16, that is, any region to be isolated from the surrounding soil and/or groundwater. Selected region 16 has a periphery 18. The transition from soil within region 16 to soil outside the region is usually gradual. Thus, if region 16 includes contaminated soil or even desirable plant nutrients, periphery 18 may represent a region of gradually decreasing concentrations rather than an abrupt transition to soil 12. Region 16 may lie completely beneath surface 14 as shown, or extend to surface 14. Depending on the size and depth of region 16, the region may lie partly in the vadose zone and partly within the lower, saturated zone, wholly within the vadose zone, or wholly within the saturated zone. Migration of contaminants from selected region 16 into region 12 can be substantially reduced by a barrier placed in accordance with the present invention (as shown in Fig. 3 and described below).

The fracture formation process begins with the installation of conduits such as boreholes 20 (Fig. 1) or pipes 120 (Fig. 8) into formation 10 by any convenient method. The conduits penetrate the soil to the depth where the barrier is to be located. Conduits may be arranged in a grid as shown in Fig. 2, or in other configurations. A cavity 22 is created and enlarged at the bottom of each conduit at the depth where the soil is to be fractures and the barrier is to be located. Cavity 22 can be enlarged mechanically, hydraulically, pneumatically, or by any other suitable technique. That is, the load bearing material is removed or displaced to form a flattened and roughly circular (ellipsoid) type cavity 22. This causes stress concentration conditions in the soil at the largest perimeter (along major axes) of the cavity 22, which in turn controls the initial location and direction of the soil fracture when the cavity 22 is pressurized. Hence the stress concentration cavities are aligned to cause the initial fracture from each cavity 22 to propagate toward adjacent cavities and create a single continuous

fracture. (Note that the major axes of cavity 22 can be oriented at various angles with respect to the conduit axis to permit contouring the shape of the planned fracture.)

Once the stress concentration cavity 22 is created, packer 24 is installed into each borehole 20 with seals located immediately above cavity 22. The packer 24 is inflated (seals not shown) against the bare wall of borehole 20 to seal the cavity 22 from the atmosphere. (Packer assemblies 24 are standard devices such as are known in the art.) Once this is completed for each borehole 20, the cavities are all rapidly and synchronously pressurized through tube 28 (part of packer) with a gaseous fracture fluid 26 until the soil fractures at each cavity at about the same time and the cracks propagates toward adjacent cavities forming fracture 30 across the entire area where the stress concentrations cavities were formed. Hence fracture 30 will connect all cavities 22 with substantially a single and continuous fracture. This process is known as preferentially fracturing, that is, creating a broad continuous fracture in soil at the desired location. Such preferential fracturing is achieved because of the selected position and alignment of stress concentrations cavities that predetermine the path of soil fracture when the soil is suddenly and synchronously pressurized at the stress concentration cavities. This process utilizes the plasticity and cohesiveness of soil as previously noted to achieve the desired fracture. Outside the control zone, the fracture may propagate in various directions and non-uniformly unless limited by such things as vent holes or subsurface walls.

Another preferred embodiment for the creation of the stress concentration cavities is illustrated in Fig. 8. Pipe 120 with a removable bottom end plug 122 is pushed or driven into the soil to the depth desired for the barrier without otherwise disturbing the soil (*in situ* installation). End plug 122 is then driven out of pipe 120 to form a small cavity in the soil beneath the pipe. Cavity 22 is then created and enlarged using the methods previously described. In this configuration, pipe 120 replaces the

borehole and packer assembly and functions as tubing 28 as shown in Fig. 1, and pipe 120 also seals to the soil by soil compaction so that cavity 22 can be pressurized. The method illustrated in Fig. 8 for creating and forming and pressurizing the stress concentration cavities is much simpler that the borehole and packer method of Fig. 1. The use of pipe 120 also eliminates any need to collect and dispose of contaminated material that is removed during a drilling process.

Once the cavities are pressurized and a continuous fracture is created, barrier fluid is injected through tube 28 or pipes 120 in a manner similar to the injection of fracture fluid though more slowly. The barrier fluid flows along fracture 30 to form a barrier 40 shown in Fig. 3. Barrier 40 has a boundary 42 with the surrounding soil 12. (Boundary 42 may be a region that contains a gradually decreasing concentration of barrier material due to factors such as the properties of the selected barrier fluid.)

The thickness of barrier 40 depends on the amount of barrier fluid injected into the fractures, the characteristics of the barrier fluid, and such other factors as will be evident to those skilled in the art. Although the barrier fluid flows primarily along the fracture plane (i.e., in the region containing fracture 30), low viscosity Newtonian fluids can be used that will penetrate into soil 12. Hence, the quantity and characteristics of the barrier fluid injected into fracture 30, as well as the locations selected for injection, can be used to control the thickness of barrier 40.

Figures 4A, 4B and 6 diagram a test that was preformed to demonstrate the procedure and illustrate additional preferred embodiments of the invention. Figure 4A is a plan view showing seven boreholes 20 arranged in a hexagonal configuration. Surrounding the boreholes is an outer row of vent holes 100. Vent holes are bare wall hole in the soil to a depth somewhat deeper than boreholes 20 or pipes 120 (depth of cavity) and are designed to intercept fracture fluid during the fracturing process and vent the fracture fluid to the atmosphere. Vent holes stop the propagation of the

fracture. Vent holes 100 allow control of the range or radial distance the fracture will propagate outside the array of stress concentration cavities 22 or control zone 112, (delineated as 114 in Fig. 4B). Fig. 4B shows the subsurface test configuration in profile view before the packers were installed. Also shown in Fig. 4A is compressor 110 used to supply pressurized air to manifold 106 for distribution to cavities 22 (Fig. 4B) by hoses 108 (and packers). The air pressure was used to synchronously pressurize all cavities 22 and initiate a soil fracture that connected all cavities 22 with a single fracture. Beyond the outer row of cavities 22 (outside the control zone 112) the fracture turned upward at a 20 to 40 degree angle to the horizontal until the fracture (and fracture fluid) reached the vent holes 100. At this point the fracture gas escaped to the atmosphere and the fracture 30 was terminated. The air pressure and airflow history during the fracturing process is shown in Figures 5A and 5B respectively.

Injection of neat cement to all cavities 22 was accomplished immediately after the fracture to allow formation of the *in situ* subsurface barrier. Excavation of the demonstration site revealed the installation of a continuous barrier, which was near uniform depth and thickness in the control zone 112. This is illustrated in the cross sectional view as Fig. 6 (from section 6B of Fig. 4) and identified as barrier 40. Outside the control zone 112, the fracture and therefore the barrier turned upward and terminated at the vent holes 100.

The demonstration showed that the fracture and barrier could be made continuous and controlled within the control zone 112. The demonstration also showed that the radial propagation of the fracture could be limited outside the control zone 112 and the fracture terminated as needed with vent holes 100. The demonstration showed that a very thin and continuous layer of barrier material could be formed. An oblique view of the excavated barrier is shown in the photograph of Fig. 7. The photograph shows the edge of the barrier, which is less than ¼ inch thick, and the top surface of the

barrier where the soil was removed. Note the continuous surface of the barrier, which was achieved, even with a thin layer of material. Thicker barrier layers would virtually assure 100% coverage by the barrier in the control zone.

Preferential fracturing of soil in region 12 may be accomplished and a barrier installed underneath the site that is to be isolated as described above. The barrier may be connected to vertical subsurface walls installed by other suitably technologies; alternatively, the barrier may be installed to substantially enclose the periphery of the site by contouring the fracture and barrier to approach the soil surface. The thickness and extent of the barrier can be controlled, thus, the barrier can cover a very large area, yet be limited in size as needed by appropriately positioned vent holes or subsurface walls. Furthermore, the configuration of the fracture ensures that the use of costly barrier materials can be minimized.

Preferably, the fracture fluid is air or some other gas that expands rapidly and causes a sudden, catastrophic failure of the soil thus utilizing the plasticity and cohesiveness of the soil to lift the soil as a unit. However, any convenient fluids that serve to preferentially fracture the soil may be used for the practice of this invention.

Following fracturing of the soil, a barrier fluid is injected into cavities 22 and fracture 30 through tubes 28 or pipes 120 (as shown in Fig. 8), or other suitable conduits. While single point injection may be adequate for some applications, multipoint injection of barrier fluid to each stress concentration cavity causes a thinner layer of barrier fluid to form as it flows along the plane of fracture 30 and consumes less barrier fluid material.

Upon solidification or curing of the barrier fluid, a barrier 40 is formed as illustrated schematically in Fig. 3. Barrier 40 is formed within the major fracture plane (indicated by fracture 30, Fig. 1) upon injection of a suitable barrier fluid.

The barrier fluid is any convenient fluid that sets, cures, solidifies, or consolidates to form a barrier having the desired characteristics. Because of the preferential placement of soil fracture 30, fluid materials with special properties may be selected for use with the invention depending on the site characteristics and the desired results.

The barrier fluid can form either a porous or a nonporous barrier 40. Barrier fluids usable with the invention include, but are not limited to, grout, Portland cement, plastics, two-component epoxy resins, silica gel, and like materials. Depending on the site characteristics, soil-penetrating (i.e., low viscosity fluids) or non-penetrating barrier fluids (i.e., Bingham fluids) may be usable with the invention. In one preferred embodiment of the invention, the barrier fluid is a Bingham fluid that flows preferentially along an interface with soils (fracture), that is, a fluid that does not penetrate into the soil grains due to the shear stresses required to move the fluid. Additional techniques may be used to install a barrier 40 without departing from the spirit of the present invention.

The optimal spacing of boreholes 20 depends on the subsurface geology of region 12, including factors such as the depth within the soil, the soil plasticity, cohesiveness, moisture content, and other soil characteristics. The spacing of cavities 22 may be relatively large but small enough to allow formation of a substantially single and continuous fracture, and hence form a substantially single and continuous barrier when the barrier fluid is injected therein.

CONCLUSIONS, RAMIFICATIONS, and SCOPE of the INVENTION

The present invention is unique in that it provides a simple method using common tools to place a large but substantially single and continuous fracture in soil at

a planned location. The invention also allows placement of a substantially single and continuous layer of material within the fracture to form a barrier or other feature that can cover a broad area at a prescribed location using a minimum of the selected material. Minimal material usage is achieved because the barrier is a single layer of nearly uniform thickness as needed to achieve the desired characteristics of the barrier.

This invention can be contrasted with an existing method (Huff, U.S. No. 5,030,036) for installation of a subsurface barrier. Huff's method utilizes multiple fractures from one location within one well at a time, with no control over where the fracture occurs or propagates. Such techniques produce a maze of fractures that may or may not overlap adequately. Without controlling the placement and extent of the fracture by preferentially stressing the soil, the soil tends to fail in a dendrite manner as noted by Keck (U.S. No. 5,536,115). The Huff method therefore uses barrier fluids that penetrate into the soil in order to try and achieve complete coverage since there is no assurance that the individual fractures connect. Injection of soil penetrating barrier fluid into each fracture requires many times the material needed for a single broad fracture and such material can be very expensive. The need for soil penetrating barrier fluid also limits the selection of materials that can be used for the barrier.

The present invention will have broad applications because it is a unique process that provides a simple method for *in situ* placement of a subsurface layer of material in soil. Furthermore the efficacy of the process minimizes both the cost of installation and the cost of materials. The ability to utilize many different barrier materials further means that many different barrier characteristics can be achieved for different applications.

As will now be evident, the above-described method can be used to form a subsurface barrier at a specific and planned location. The method can also be used to form different layers of material at different elevations and locations in the soil. The

formed barrier can be configured to lie within a narrow area, for example, between clay layers, or over a broad area, reaching from near the soil surface to deep within the subsurface. A barrier installed according to the present invention can be used with other existing technologies, for example, with the installation of vertical subsurface walls in the soil and caps for total encapsulation of a section of the soil.

It will be apparent to those skilled in the art that many changes and substitutions can be made to the preferred embodiment herein described without departing from the spirit and scope of the present invention as defined by the appended claims.